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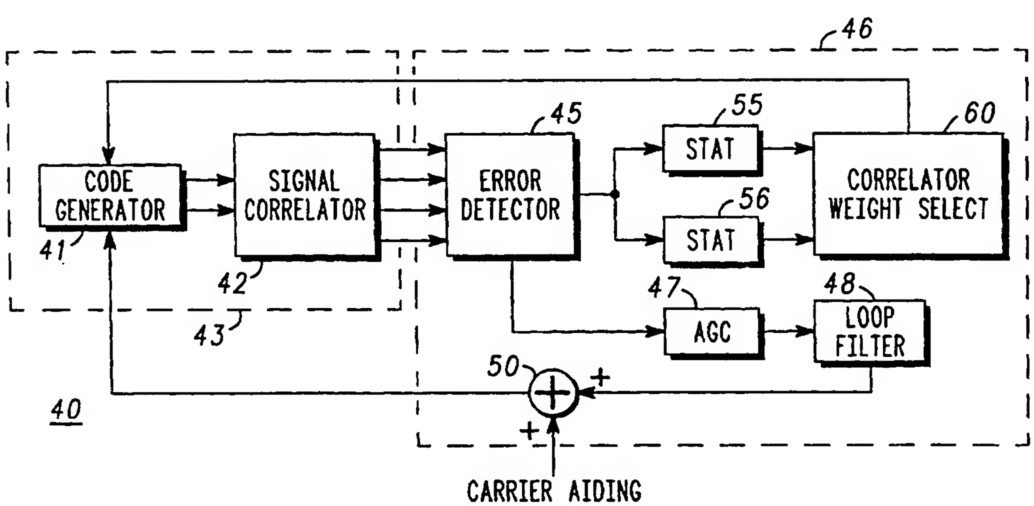
(54) Title: ADAPTIVE DELAY LOCK LOOP TRACKING



(57) Abstract: An adaptive delay lock loop for tracking a direct sequence, spread spectrum signal is disclosed which includes a reference code generator (41) having adjustable weighted early and late taps. Signals from the early and late taps are combined to generate an E-L reference code output signal. A signal correlator (42) and error detector (45) are coupled to receive and correlate a direct sequence, spread spectrum signal to be tracked and prompt and E-L reference code output signals from the reference code generator (41). First and second code loop error statistics generators (55, 56) are connected to receive an error signal from the signal correlator (42) and error detector (45) and generate first and second error statistics signals for adjusting the weight of the adjustable weighted early and late taps. Additional early and late taps can be added and they can be adjustable or set to an initial weight.

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ADAPTIVE DELAY LOCK LOOP TRACKING

Field of the Invention

The present invention pertains to delay lock loops and more specifically to adaptive delay lock loops for use in tracking GPS pseudo random codes and the like.

Background of the Invention

In applications where the positioning errors induced by Selective Availability (SA) and ionospheric refraction can be compensated, Global Positioning System (GPS) position error is generally determined by the magnitude of the residual noise and multipath error in the pseudo range measurements generated by the GPS receiver. Such applications include differential GPS, where the combined effects of SA and ionospheric delay are explicitly estimated using a separate GPS receiver at a known location, and attitude determination, where pseudo range measurements to an individual satellite can be differenced and filtered (in an effort to resolve integer ambiguities associated with differential carrier phase), thereby eliminating the error contributions of SA and the ionosphere.

Currently, these multipath and noise error corrections are partially achieved by means of a Delay Lock Loop (DLL) within the GPS receiver. The noise and multipath content of the DLL used within the GPS receiver are strongly dependent upon the early/late spacing, i.e., the sampling of the code sequence relative to prompt, or on-time spacing within the loop. This motivates the use of narrow spacing: multipath errors cannot exceed the magnitude of the spacing, and the

noise variance at the output of the discriminator is proportional to the spacing, as described in "Theory and Performance of Narrow Correlator Spacing in a GPS Receiver", A.J/ Van Dierendonck et al., Journal of the Institute of Navigation, Fall 1992. However it is generally unwise to use narrow spacing all the time, since it increases the number of cells in the search region required for GPS signal acquisition, and so can increase the acquisition time of the receiver. This undesirable effect is particularly noticeable in environments where the number of search cells is increased by a large Doppler uncertainty (e.g. in a spaceborn GPS receiver). This fundamental tradeoff is dealt with currently by selecting different spacings for acquisition and track, by designing the correlators to have dynamically selectable delays, as described in U.S. Patent No. 5,101,416, entitled "Multi-Channel Digital Receiver for Global Positioning System", issued 31 March 1992, and using a predetermined wide delay during acquisition, and a predetermined narrow delay during track, as described in U.S. Patent No. 5,390,207, entitled "Pseudorandom Noise Ranging Receiver which Compensates for Multipath Distortion by Adjusting the Time Delay Spacing Between Early and Late Correlators", issued 14 February 1995.

The major problem with the above described systems is that the DLL tracking parameters are preselected. Preselection is typically done conservatively, with large, fixed spacing (e.g., one-half chip) used during code acquisition and pull-in, and small, fixed spacing (e.g., one-tenth chip) used for code tracking. Use of multiple weighted spacings for DLLs was examined to extend the tracking ability of the loop in degraded signal environments induced by jamming, as described in Correlation Tracking, W.M. Bowles, PhD Dissertation, MIT Department of Aeronautics and Astronautics, June 1980. However, the DLL modification

discussed in this dissertation degrade the noise and multipath performance of the loop.

Therefore, an alternate approach to the design of the DLL is sought which permits a continuously controlled, adaptive correlator spacing. Multiple spacings with continuously adjusted weights are used to minimize the tracking error within the loop. When the loop is experiencing significant dynamic lag, the weighting will adapt to minimize this error effect; on the other hand, as a steady state tracking condition is approached, the weighting will adapt to minimize the residual noise and multipath in the loop.

Brief Description of the Drawings

Referring to the drawings:

FIG. 1 is a generalized system block diagram for a GPS receiver;

FIG. 2 is a simplified block diagram of a GPS tracking loop;

FIGs. 3A, 3B, 3C, and 3D illustrate the construction of early and late codes in a prior art DLL tracking loop;

FIG. 4 illustrates a representative autocorrelation function for the prior art DLL tracking loop;

FIG. 5 illustrates the discriminator function, or S curve, for the prior art DLL tracking loop;

FIG. 6 is a simplified block diagram of a DLL code loop in accordance with the present invention;

FIG. 7 is a schematic representation of a reference code generator in accordance with the present invention;

FIGs. 8A, 8B, and 8C illustrate optimal code generation in a DLL tracking loop in accordance with the present invention;

FIG. 9 illustrates a representative autocorrelation function for the DLL tracking loop of the present invention; and

FIG. 10 illustrates the discriminator function, or S curve, for the DLL tracking loop in accordance with the present invention.

Detailed Description of the Drawings

Referring specifically to FIG. 1, a generalized system block diagram of a GPS receiver 10 is illustrated. Receiver 10 includes an antenna 11 for receiving GPS signals from a plurality of GPS satellites and supplying the received signals to an RF front end 12. As is known in the art, front end 12 provides the required filtering and mixing to supply the received signals as intermediate frequency (IF) signals to a channel signal processing block 15. Generally, a GPS receiver can be in a position to receive signals from several satellites simultaneously and, as is known by those skilled in the art, the commercial GPS signals are all at the same carrier frequency, with each satellite identified by a unique code. Channel signal processing block 15 communicates with a microprocessor 16 which includes software that controls and processes data from channel signal processing block 15 to measure or correlate a reference code signal with a desired one of the various received unique codes. In this fashion the software can, for example, determine the distance to a specific satellite and, eventually, the position of the GPS receiver.

Referring additionally to FIG. 2, a simplified block diagram of a GPS tracking loop 20, included within channel signal processing block 15 and microprocessor 16 of FIG. 1, is illustrated. Loop 20 receives an input signal s(t) at

one input of a mixer 21 and a local oscillator signal, $\cos(w_o t)$, from a carrier NCO 22 at a second input. An output of mixer 21 is supplied through a carrier loop filter 23 to control NCO 22, thereby closing the carrier loop. The output of mixer 21 is also supplied to an input of an early minus late (E-L) mixer 25 and to an input of a prompt mixer 26. The output of NCO 22 is also applied to a C/A code generator 27, representing an aiding signal supplied to the DLL from carrier tracking.

C/A code generator 27 provides an E-L signal to a second input of mixer 25, the output of which is applied through a code loop filter 28 to control C/A code generator 27. C/A code generator 27 also supplies a prompt signal to a second input of mixer 26, the output of which is supplied to a data demodulator 30. The output of data demodulator 30 is supplied as a data output to any subsequent equipment, such as microprocessor 16 in FIG. 1. C/A code generator 27, mixer 25, and code loop filter 28 form the DLL which generates a reference code that is correlated or compared with the incoming or received signal, s(t).

In prior art DLLs, such as those described in the above referenced patents ('416 and '207), apparatus and a method of reducing multipath distortion consist of a first wide spacing in the code loop response for acquisition of the code signal and a second narrow spacing for tracking of the code signal. Referring additionally to FIG. 3, waveform (FIG. 3A) is a representation of a short portion of the received GPS pseudo random, spread spectrum code. Waveform (FIG. 3B) is a representation of a similar portion of the prompt generated reference code (input signal to mixer 26 from C/A code generator 27 in FIG. 2). Waveform (FIG. 3C) is a representation of the E-L generated code (input signal to mixer 25 from C/A code generator 27 in FIG. 2) with wide spacing utilized for tracking in prior art DLLs. Generally, the wide spacing illustrated in waveform (FIG. 3C) is a chip wide, i.e. one half chip wide on either side of the code edge. Once acquisition is achieved,

the spacing is reduced to something close to one half chip, i.e. one quarter chip on either side of the code edge, as illustrated in waveform (FIG. 3D).

Referring to FIG. 4, an ideal autocorrelation function for the C/A code is illustrated, indicating its peak value, corresponding to perfect correlation, and its linear decay to a value near zero for a full chip delay. The E-L code wide spacing in the typical DLL discriminator is represented by points 35 and 36 on the autocorrelation function curve. Because a large amount of the autocorrelation function curve is utilized, acquisition of the GPS pseudo random, spread spectrum signal can occur, however, residual noise and multipath errors are maximum. Once acquisition is achieved, the spacing is reduced to points 37 and 38 for tracking, which reduces residual noise and multipath errors. In FIG. 5, the discriminator or S curve for a prior art DLL tracking loop is illustrated, corresponding to a minimum E-L spacing; note the decay to zero at slightly less than one full chip of delay. It is this decay which achieves multipath suppression for delays outside of this range.

Turning now to FIG. 6, a simplified block diagram of a delay locked code loop 40 in accordance with the present invention is illustrated. Code loop 40 includes a reference code generator 41 which, in this specific embodiment, supplies an E-L code and a prompt code to a signal correlator 42. Signal correlator 42 supplies in-phase and quadrature E-L code signals and in-phase and quadrature prompt code signals to an error detector 45. Here it should be noted that in the preferred embodiment code generator 41 and correlator 42 are included as hardware on an ASIC chip, denoted by broken line box 43, and the remaining components (including error detector 45) are included in signal processing software within a microprocessor or the like, denoted by broken line box 46.

The error signal at the output of error detector 45 is supplied through an AGC circuit 47 and a loop filter 48 to a summing junction 50. As will be understood by those skilled in the art, a carrier aiding signal is supplied to summing junction 50 to aid DLL code loop 40 in locking onto a correct or desired direct sequence, spread spectrum signal, such as a selected one of several GPS pseudo random, spread spectrum signals. The output signal from summing junction 50 is supplied or fed back to an input of code generator 41 to control code generator 41 for acquisition and tracking.

The error signal at the output of error detector 45 is also supplied to the inputs of a pair of code loop error statistics generators 55 and 56. Statistics generators 55 and 56 have different bandwidths, with statistics generator 55 having a bandwidth which is large or wide relative to the bandwidth of DLL code loop 40 and statistics generator 56 having a bandwidth which is narrow relative to the bandwidth of DLL code loop 40. Code loop 40 incorporates gain adaption which is driven by the generation of code loop error statistics in the separate bandwidths of statistics generators 55 and 56.

Output signals from code loop error statistics generators 55 and 56 are supplied to a correlator weight selector 60, which supplies weight selector signals to code generator 41, as will be described in more detail presently. Large error statistics in the bandwidth of statistics generator 55, which is large or wide relative to the bandwidth of DLL code loop 40, are generally indicative of residual tracking errors in DLL code loop 40. Error statistics in the bandwidth of statistics generator 56, which is narrow relative to the bandwidth of DLL code loop 40, are generally indicative of residual noise and multipath errors in DLL code loop 40. Large error statistics in the narrow band (statistics generator 56) drive weight selector 60 to minimize residual noise and multipath errors.

Referring additionally to FIG. 7, a schematic representation is illustrated of a portion of reference code generator 41 in accordance with the present invention. Here it should be understood that reference code generator 41 includes a code synthesizer (not shown) which is controlled by the feedback signal from mixer 50. The output or synthesized code signal is supplied to code input 65 in FIG. 6 and the various taps, designated t_{-N} through t_0 and through t_N, are positioned at various points or times along a chip of the synthesized code signal. Here it should be understood that t_0 is the prompt code output and there are a plurality (t_N) of early code taps and a similar plurality (t_{-N}) of late code taps. Further, each early and late code tap has associated therewith a weighting function k, with the associated weighting functions being designated with a sub-numeral similar to the associated tap, i.e. k_N through k_{-N}. Each of the early and late weighting functions k_N through k_{-N}, are adjustable by signals from weight selectors 60.

Before explaining how to adjust the gains as a function of the code loop error statistics computed in real time, the noise and multipath performance of this formulation will be described. The noise in a conventional (i.e. single E-L) DLL can be expressed as:

$$n_{IE/L} = \cos (T - T_{est}) \geq n_I \; [c(t - \Omega + \Omega_{est} - \ni) - c(t - \Omega + \Omega_{est} + \ni)] \; dt \qquad (1)$$

$$n_{QE/L} = \sin(T - T_{est}) \geq n_Q[c(t - \Omega + \Omega_{est} - \ni) - c(t - \Omega + \Omega_{est} + \ni)]\, dt$$

(2)

where: T is the phase of the L1 carrier;

T_{est} is the phase lock loop's estimate of carrier phase;

Ω is the range delay induced in the C/A code;

Ω_{est} is the DLL's estimate of the range delay;

n_I and n_Q are the in-phase and quadrature components of the noise, respectively;

$\ni$ is the spacing of the DLL;

and c is the GPS C/A code.

Note that it is assumed that both in-phase (I) and quadrature (Q) correlations are used in the loop (i.e. the loop is designed with some level of non-coherence). Because the C/A codes which are differenced within each integral are identical except for the intentional DLL shift $\ni$, much of the noise cancels. The residual noise variance is proportional to the spacing $\ni$. In a conventional DLL, therefore, the residual noise is minimized with minimum spacing.

For DLL loop 40 of FIG. 6, which uses multiple spacings in forming the reference code, equations (1) and (2) become:

$$n_{IE/L} = \cos(T - T_{est})\, f\, k_i\{\geq n_I\, [c(t - \Omega + \Omega_{est} - \ni_i) - c(t - \Omega + \Omega_{est} + \ni_i)]\, dt\}$$

(3)

$$n_{QE/L} = \sin(T - T_{est})\ ƒ\ k_i\{\geq n_Q[c(t - \Omega + \Omega_{est} - \text{э}_i) - c(t - \Omega + \Omega_{est} + \text{э}_i)\ ]\ dt\}$$

(4)

The indicated summations are performed for i = 1, . . ., N. Note that the gains are assumed to be anti-symmetric, i.e. ki = -ki. The noise variances associated with the new reference code can be evaluated, and are given by:

$$\varsigma^2{}_{IE/L} = 2T\ \varsigma^2{}_{nI}\ \cos^2(T - T_{est})\ \{\ ƒ\ k^2{}_i w_i + 26\, k_i k_j \min(w_i, w_j)\}$$

(5)

$$\varsigma^2{}_{QE/L} = 2T \varsigma^2{}_{nQ}\ \sin^2(T - T_{est})\ \{\ ƒ\ k^2{}_i w_i + 26\, k_i k_j \min(w_i, w_j)\}$$

(6)

where: $w_i = \text{э}_i / C$;

T is the PreDetection integration Interval (PDI);

$\varsigma^2{}_{nI}$ and $\varsigma^2{}_{nQ}$ are the noise variances associated with n_I and n_Q, respectively;

and C is the C/A code chip size.

Note that the second summation which appears in the expressions for the noise variances is performed only over combinations (not permutations) of the indices for which i and j are not equal. Selection of the weightings which minimize the resultant noise variances in equations (5) and (6) can be obtained by minimizing the summation.

To gain insight into the selection of weights which minimize the noise variance, each early and late tap in FIG. 7 is assumed to be separated by less than 0.25 of a chip and, in this preferred embodiment by one-tenth of a C/A code chip interval, and, for simplicity, only three pairs of weightings will be allowed to be nonzero: k_1, k_{-1}, k_3, k_{-3}, k_5, and k_{-5}. Each set of gains will, of course, be anti-symmetric, i.e. $k_i = -k_{-i}$. Since smaller correlator spacings produce lower residual noise, k_1 will be assumed to be one. The resulting expression to be minimized is therefore:

$$\min_{(k_3,k_5)}\{1 + 2k_3 + 2k_5 + 3k_3^2 + 6k_3k_5 + 5k_5^2\} \quad (7)$$

Taking partial derivatives of equation (7) with respect to the gains results in the following equations:

$$2 + 6k_3 + 6k_5 = 0 \quad (8)$$

$$2 + 6k_3 + 10k_5 = 0 \quad (9)$$

which results in the solution $k_3 = -1/3$ and $k_5 = 0$. To determine the reduction in noise variance which is achieved relative to a fixed spacing, these values can be substituted into the noise expressions, and compared with a conventional narrow

spacing. A noise variance reduction of 33% is achieved. Also, the improvement in noise performance does not degrade signal tracking capabilities.

To gain insight into the ability of DLL code loop 40 to attenuate multipath errors, assume a single, specular multipath reflection with a constant reflective coefficient. A detailed analytical treatment is not required, since the multipath content of the correlation performed by DLL code loop 40 can be viewed as the weighted sum of the multipath content of separate, DLLs with fixed spacings of 0.1 and 0.3 (for the example described above). Assuming that multipath delays within the chip spacing appear directly in the output of the correlation, the weightings derived previously to attenuate noise will also reduce multipath by 33%, since the multipath delay error induced by the 0.3 spacing will be subtracted from that induced by the 0.1 spacing. However, multipath delays greater than 0.1 chip will produce error for the weighted correlator spacings, and will not for the fixed spacings. It is anticipated that DLL code loop 40 can be constructed with a plurality of fixed early and late spaced taps or the taps can be weighted as described. In environments where multipath reflections are expected to be within 0.1 chip (e.g. a spacecraft environment), DLL code loop 40 should outperform the multiple fixed 0.1 chip DLL.

Given the improvements in noise and multipath attenuation for DLL code loop 40 when an appropriate set of gains is selected, the real-time adaptation of the gains can now be addressed. The adaptation is based on the magnitude and frequency content of the code loop error signal, as computed below;

$$e_{code} = I_{opt}\,\mathrm{sign}(I_p) + Q_{opt}\,\mathrm{sign}(Q_p) \qquad (10)$$

The code loop error signal computed by equation (10) represents the error which exists in DLL code loop 40, as measured by the loop itself. As such it represents the combined effects of noise, multipath, receiver clock induced error, and transient error induced by dynamics. The presence of significant noise and/or multipath leads to a selection of gains as described above, i.e., with the largest gain applied to the smallest spacing, and the other gains selected to achieve the desired suppression. Errors induced by the receiver clock and/or dynamics, on the other hand, must be removed by the tracking loop, and so cannot be suppressed by the code loop discriminator. If the code loop bandwidth is properly selected, and maximum use is made of dynamic aiding sources (e.g., the carrier tracking loop will generally be used to aid code tracking, and remove its requirements to track dynamics), errors induced by the receiver clock and dynamics can be kept within the desired minimum spacing (e.g., 0.1 chip). Thus, the primary adaptation of the weights will be as the loop approaches steady-state tracking conditions from an initial acquisition. However, momentary loss of carrier lock due to excessive dynamics or degraded signal to noise ratio can be detected and used to adjust the weightings and maintain lock in situations where a conventional DLL could lose track.

Following signal acquisition, a large linear range is utilized (dictating $k_5 = 1$), with the other gains again set to minimize the residual noise and multipath. Assuming that k7 and k9 are allowed to be nonzero, the minimum noise condition from equations (5) and (6) produces the following solution for the gains: $k_7 = -10/14$ and $k_9 = 0$. This gain selection leads to a noise variance reduction of 71%. Then the gain adaptation will be based on the mean and variance of the code loop error signal, as computed in two separate bandwidths. The first bandwidth is large

or wide with respect to the code loop bandwidth (e.g., 50 Hz to 100 Hz), and is used to measure the level of noise and multipath, i.e., sources of error with a frequency content which is high relative to the error sources which the loop can track. The second bandwidth is small or narrow relative to the code loop bandwidth (e.g., 0.1 Hz to 1 Hz), and so measures residual error which the loop is expected to remove. As the error is distributed from the second bandwidth to the first, implying that the error is dominated by noise and multipath, the gains are adapted to the set which minimizes these error sources. The rate of gain adaptation is determined by code loop error statistics generators 55 and 56: as the residual error in the first bandwidth falls below a certain spacing, gains applied to larger spacings are set to small values. On the other hand, should sudden, unexpected dynamics shift code loop error statistics generators 55 and 56 to the second bandwidth, the gains applied to larger spacings become nonzero.

Referring additionally to FIGs. 8 A-C, waveform (FIG. 8A) is a representation of a short portion of a direct sequence, spread spectrum signal, such as a GPS pseudo random, spread spectrum signal. Waveform (FIG. 8B) is a representation of a similar portion of the prompt generated reference code, generally as it appears on tap t0 of FIG. 7. Waveform (FIG. 8C) is a representation of the E-L generated code in DLL code loop 40 with multiple 0.1 chip taps. As described above, in the preferred embodiment the taps are weighted and the weights are continuously adjusted to minimize residual noise and multipath errors in DLL code loop 40. Referring additionally to FIG. 9, a representative autocorrelation function for DLL code loop 40 is illustrated. The various taps appear in the waveform as points with taps t_1 and t_{-1} being designated 70 and 71, respectively; taps t_2 and t_{-2} being designated 72 and 73, respectively; and taps t_N and t_{-N} being designated 74 and 75, respectively. It should be

understood by those skilled in the art that more or less taps can be utilized with the complexity of the design being determined by the number of taps or coder positions. Once an appropriate number of taps has been selected for the application/environment, an optimal set of weightings can be found. FIG. 10 illustrates the shape of the discriminator or S curve, for three taps and the weight selection optimized for multipath and noise reduction; note the very significant differences with prior art (FIG. 5). The more rapid decay to zero is evidence of the potential multipath suppression achieved by an adaptive delay code loop in accordance with the present invention.

Thus, a method and apparatus for improved tracking of direct sequence, spread spectrum signals, such as GPS pseudo random codes, has been disclosed. The new method and apparatus result in improvements in signal tracking with significant reduction of noise and multipath errors. In the preferred embodiment, the improved signal tracking is accomplished by constructing an optimal reference code for correlation, and continuously adapting the optimal reference code as a function of tracking state. The present invention has a substantial advantage over prior art tracking loops in that it avoids any preselection of the DLL tracking parameters, that is, the parameters which control the DLL are adapted continuously as a function of the statistics of the loop error signal (i.e., the output of the code loop discriminator).

Basically, the invention includes the generation and use of an "optimal" reference code for correlation using multiple, weighted spacings of a direct sequence, spread spectrum signal. Further, the invention includes the adaptation of the spacing weightings continuously as a function of the tracking state of the loop, as determined by error statistics generated in real-time.

While we have shown and described specific embodiments of the present invention, further modifications and improvements will occur to those skilled in the art. We desire it to be understood, therefore, that this invention is not limited to the particular forms shown and we intend in the appended claims to cover all modifications that do not depart from the spirit and scope of this invention.

CLAIMS

1. An adaptive delay lock loop for tracking a direct sequence spread spectrum signal, the adaptive delay lock loop comprising:

a reference code generator having a control input, a prompt reference code output, and an E-L reference code output, the reference code generator including a plurality of weighted early taps and a plurality of weighted late taps for sampling a direct sequence, spread spectrum code at fractions of a chip of the direct sequence spread spectrum code, output signals from the weighted early and late taps being combined to generate an E-L reference code output signal;

a signal correlator and error detector coupled to the prompt reference code output for receiving a prompt reference code signal and coupled to the E-L reference code output for receiving an E-L reference code signal, the signal correlator and error detector being designed to use the E-L reference code signal and the prompt reference code signal to correlate with a direct sequence, spread spectrum signal to be tracked and provide an error signal;

and the error signal being coupled to the control input of the reference code generator.

2. An adaptive delay lock loop as claimed in claim 1 wherein the plurality of weighted early taps and the plurality of weighted late taps for sampling the direct sequence spread spectrum code at fractions of the chip of the direct sequence spread spectrum code each include spacings less than 0.25 of a chip.

3. An adaptive delay lock loop as claimed in claim 1 wherein the plurality of weighted early taps and the plurality of weighted late taps are each adjustable.

4. An adaptive delay lock loop as claimed in claim 3 including in addition first and second code loop error statistics generators connected to receive the error signal from the signal correlator and error detector and to generate first and second error statistics signals for adjusting the plurality of adjustable weighted early taps and the plurality of adjustable weighted late taps.

5. An adaptive delay lock loop as claimed in claim 4 including in addition a correlator weight selector coupled to receive the first and second error statistics signals and having an output coupled to the plurality of adjustable weighted early taps and the plurality of adjustable weighted late taps.

6. An adaptive delay lock loop as claimed in claim 4 wherein the adaptive delay lock loop has a code loop bandwidth, the first code loop error statistics generator has a bandwidth which is larger or broader than the code loop bandwidth and the second code loop error statistics generator has a bandwidth which is smaller or narrower than the code loop bandwidth.

7. An adaptive delay lock loop as claimed in claim 5 wherein the plurality of weighted early taps and the plurality of weighted late taps are each connected to receive a different sample of a chip of the direct sequence, spread spectrum code.

8. An adaptive delay lock loop as claimed in claim 7 wherein the plurality of weighted early taps and the plurality of weighted late taps each include an adjustable weight for weighting each of the different samples of the chip of the direct sequence, spread spectrum signal.

9. An adaptive delay lock loop as claimed in claim 8 wherein the adjustable weights are coupled to the correlator weight selector.

10. An adaptive delay lock loop as claimed in claim 9 wherein the adjustable weights are coupled to the correlator weight selector and continuously adjusted to minimize residual noise and multipath errors in the adaptive delay lock loop.

11. An adaptive delay lock loop for tracking a direct sequence, spread spectrum signal, the adaptive delay lock loop comprising:

a reference code generator having a control input, an E-L reference code output, and a prompt reference code output, the reference code generator including an adjustable weighted early tap and an adjustable weighted late tap, output signals from the early and late taps being combined to generate an E-L reference code output signal on the E-L reference code output;

a signal correlator and error detector coupled to the prompt reference code output for receiving a prompt reference code signal and coupled to the E-L reference code output for receiving an E-L reference code signal, the signal correlator and error detector being designed to use the E-L reference code signal and the prompt reference code signal to correlate the prompt reference code signal with a direct sequence spread spectrum signal to be tracked and provide an error signal;

first and second code loop error statistics generators connected to receive the error signal from the signal correlator and error detector and to generate first and second error statistics signals; and

a correlator weight selector coupled to receive the first and second error statistics signals and having an output coupled to the adjustable weighted early tap and the adjustable weighted late tap for adjusting the weight of the adjustable weighted early tap and the adjustable weighted late tap.

12. An adaptive delay lock loop as claimed in claim 11 wherein the adaptive delay lock loop has a code loop bandwidth, the first code loop error statistics generator has a bandwidth which is larger or broader than the code loop bandwidth and the second code loop error statistics generator has a bandwidth which is smaller or narrower than the code loop bandwidth.

13. An adaptive delay lock loop as claimed in claim 11 wherein the adjustable weighted early and late taps each sample the direct sequence spread spectrum code at fractions of a chip of the direct sequence spread spectrum signal.

14. A GPS receiver including an adaptive delay lock loop for tracking a GPS pseudo random, spread spectrum signal, the adaptive delay lock loop comprising:

a reference code generator having a control input and providing prompt and E-L reference code output signals, the reference code generator including a plurality of adjustable weighted early taps and a plurality of adjustable weighted late taps, output signals from the early and late taps being combined to generate the E-L reference code output signal;

a signal correlator and error detector coupled to receive a GPS pseudo random, spread spectrum signal to be tracked and the prompt and E-L reference code output signals from the reference code generator, the signal correlator and

error detector being designed to use the prompt and E-L reference code signals to correlate the GPS pseudo random, spread spectrum signal with the prompt reference code signal and provide an error signal;

first and second code loop error statistics generators connected to receive the error signal from the signal correlator and error detector and to generate first and second error statistics signals; and

a correlator weight selector coupled to receive the first and second error statistics signals and having an output coupled to the plurality of adjustable weighted early taps and the plurality of adjustable weighted late taps for adjusting the adjustable weighted early and late taps.

15. A GPS receiver including an adaptive delay lock loop as claimed in claim 14 wherein the plurality of adjustable weighted early taps and the plurality of adjustable weighted late taps are each connected to receive a different sample of a chip of the GPS pseudo random, spread spectrum code.

16. A GPS receiver including an adaptive delay lock loop as claimed in claim 15 wherein the plurality of adjustable weighted early taps and the plurality of adjustable weighted late taps each include an adjustable weight for weighting each of the different samples of the chip of the GPS pseudo random, spread spectrum code.

17. A GPS receiver including an adaptive delay lock loop as claimed in claim 16 wherein the adjustable weights are coupled to the correlator weight selector.

18. A GPS receiver including an adaptive delay lock loop as claimed in claim 17 wherein the adjustable weights are coupled to the correlator weight selector and continuously adjusted to minimize residual noise and multipath errors in the adaptive delay lock loop.

19. A method of tracking a direct sequence spread spectrum signal comprising the steps of:

providing an adaptive delay lock loop including a reference code generator having a control input, a prompt reference code output signal, and an E-L reference code output signal, the reference code generator including an adjustable weighted early tap and an adjustable weighted late tap, output signals from the early and late taps being combined to generate the E-L reference code output signal;

receiving a direct sequence spread spectrum signal and correlating the direct sequence spread spectrum signal with the prompt and E-L reference code signals from the reference code generator and providing an error signal;

generating first and second error statistics signals from the error signal; and

adjusting the adjustable weighted early tap and the adjustable weighted late tap using the first and second error statistics signals to minimize residual noise and multipath errors in the adaptive delay lock loop.

20. A method of tracking a direct sequence, spread spectrum signal comprising the steps of:

providing an adaptive delay lock loop including a reference code generator having prompt and E-L reference code output signals, the reference code generator including a plurality of weighted early taps and a plurality of weighted

late taps, combining output signals from the early and late taps to generate the E-L reference code output signal;

receiving a direct sequence, spread spectrum signal and correlating the received signal with the prompt and E-L reference code outputs from the reference code generator and providing an error signal; and

adjusting the reference code generator, using the error signal, to reduce errors in the step of correlating the received signal with the prompt and E-L reference code outputs.

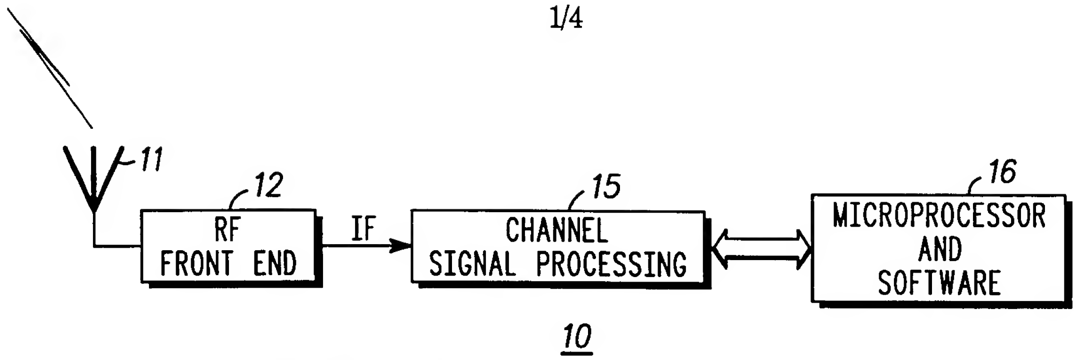


FIG. 1

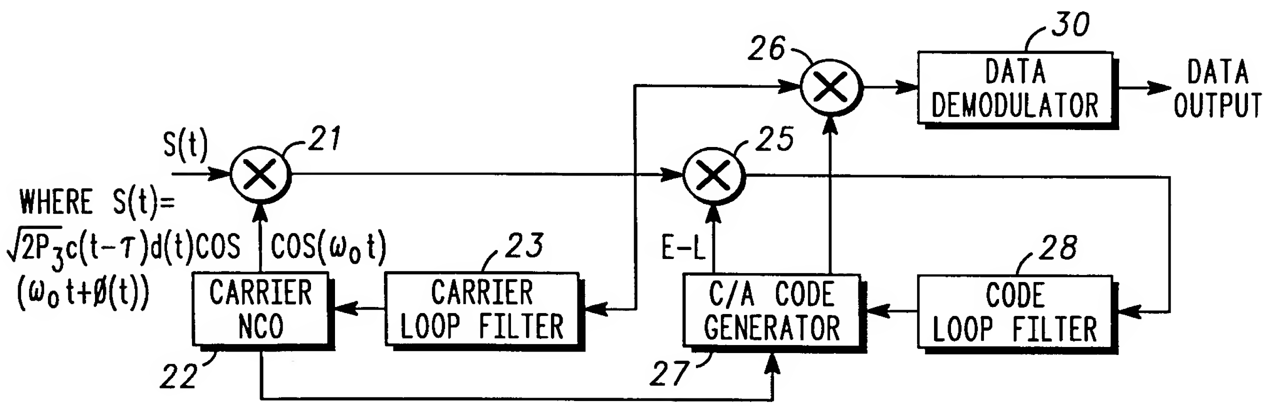


FIG. 2 20

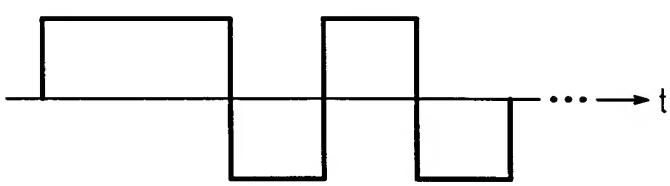


FIG. 3A
-PRIOR ART-

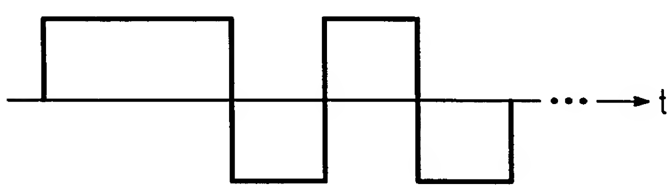


FIG. 3B
-PRIOR ART-

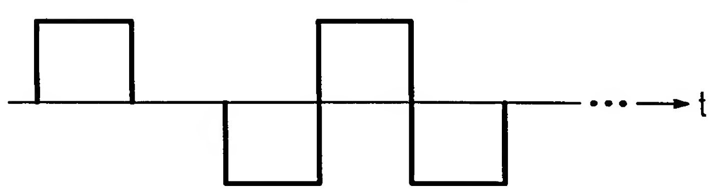


FIG. 3C
-PRIOR ART-

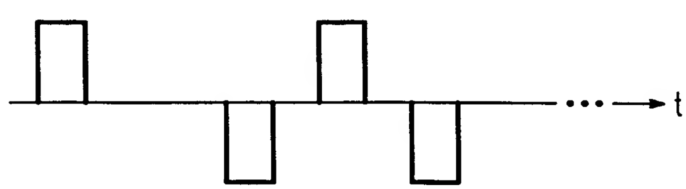
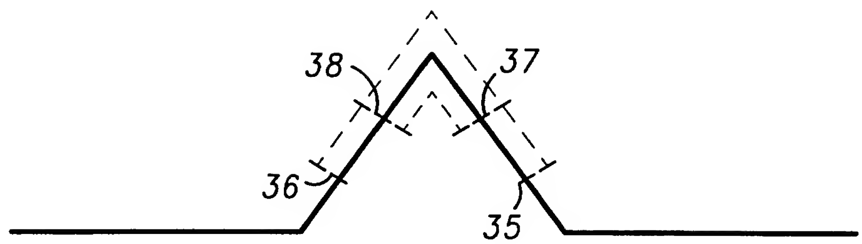


FIG. 3D
-PRIOR ART-



-PRIOR ART-

FIG. 4

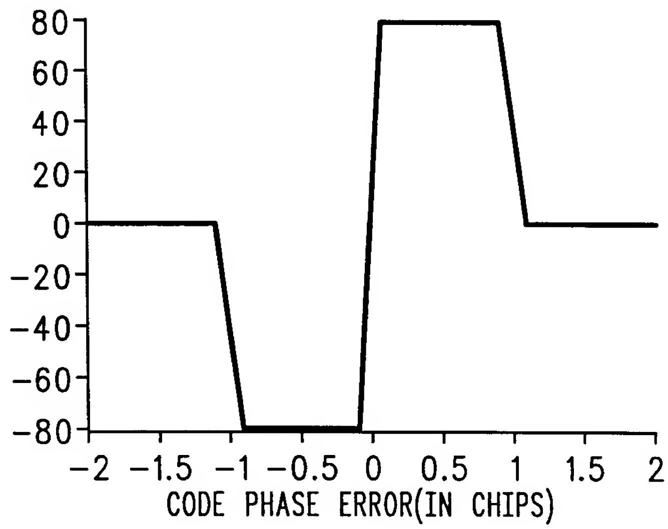


FIG. 5

-PRIOR ART-

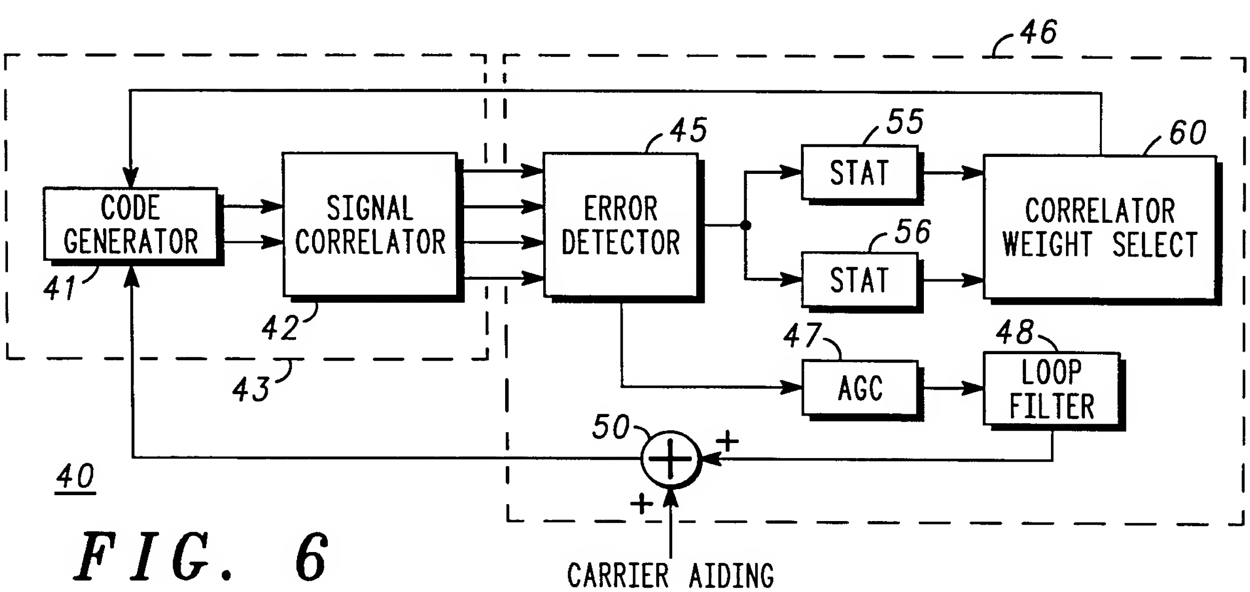


FIG. 6

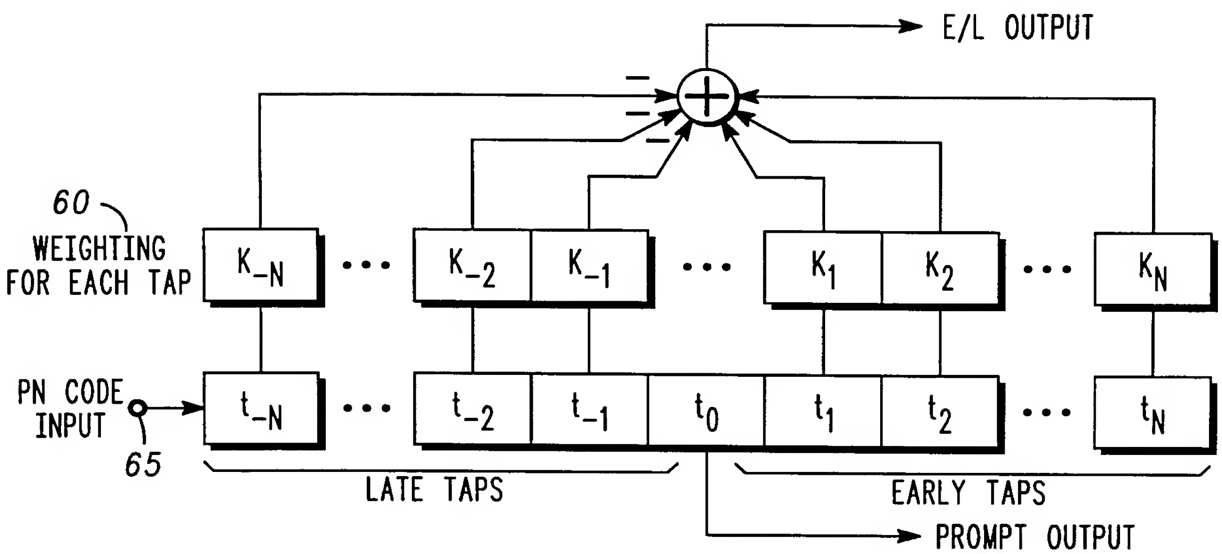


FIG. 7

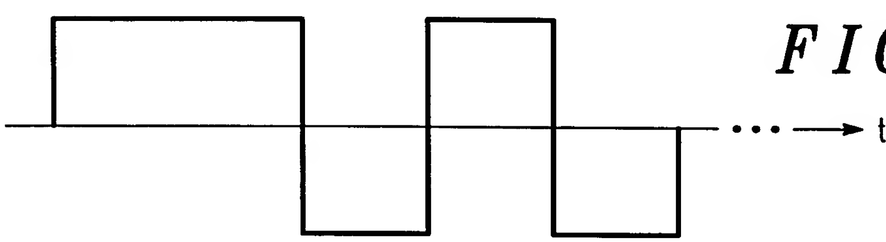


FIG. 8A

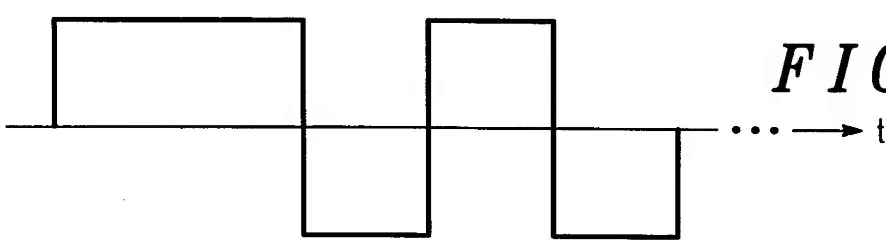


FIG. 8B

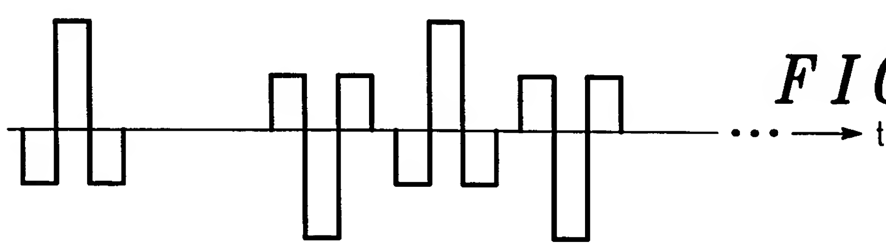


FIG. 8C

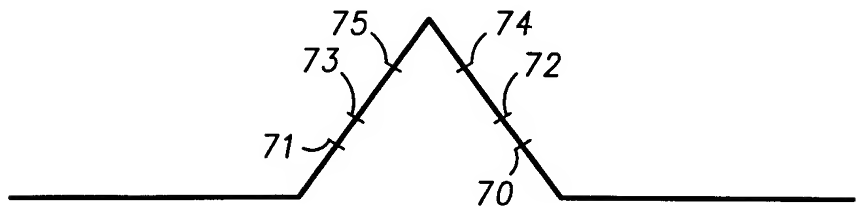

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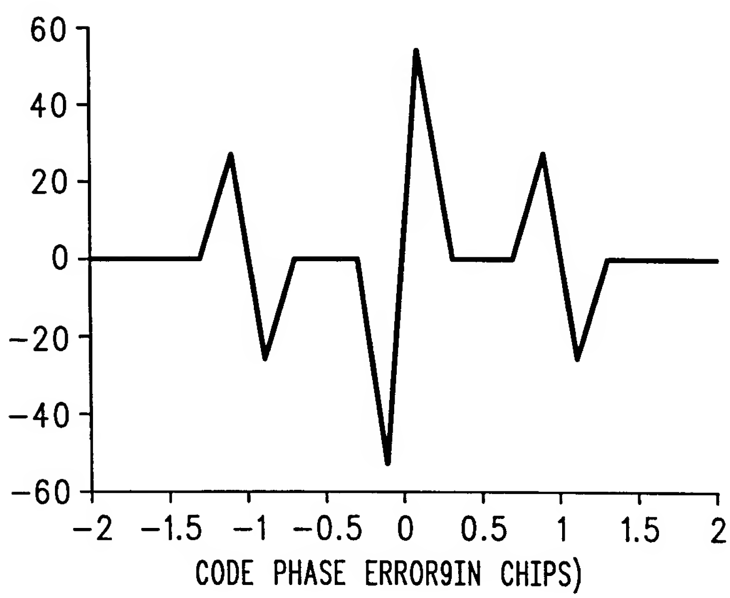
FIG. 9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2
CODE PHASE ERROR9IN CHIPS)

FIG. 10

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 00/15849

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G01S1/04 H04B1/707

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G01S H04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, INSPEC, WPI Data, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 97 44682 A (TRIMBLE NAVIGATION LTD) 27 November 1997 (1997-11-27) abstract page 7, line 8 -page 12, line 2 figures	1,11,14, 19,20
A	US 5 850 420 A (RENARD ALAIN ET AL) 15 December 1998 (1998-12-15) abstract column 3, line 29 -column 4, line 32	1,11,14, 19,20

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
28 September 2000	17/10/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Roost, J

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	EL-TARHUNI M G ET AL: "PERFORMANCE ANALYSIS FOR AN ADAPTIVE FILTER CODE-TRACKING TECHNIQUEIN DIRECT-SEQUENCE SPREAD-SPECTRUM SYSTEMS" IEEE TRANSACTIONS ON COMMUNICATIONS,US,IEEE INC. NEW YORK, vol. 46, no. 8, 1 August 1998 (1998-08-01), pages 1058-1064, XP000782283 ISSN: 0090-6778 the whole document ---	1,11,14, 19,20
A	US 5 808 582 A (WOO RICHARD KAI-TUEN) 15 September 1998 (1998-09-15) abstract column 4, line 16 -column 5, line 50 figure 7 ---	1,11,14, 19,20
A	US 5 390 207 A (FENTON PATRICK ET AL) 14 February 1995 (1995-02-14) cited in the application abstract column 3, line 17 - line 57 ---	1,11,14, 19,20
A	US 5 101 416 A (FORD THOMAS J ET AL) 31 March 1992 (1992-03-31) cited in the application abstract column 2, line 47 -column 3, line 60 ---	1,11,14, 19,20
A	VAN DIERENDONCK A J ET AL: "Theory and performance of narrow correlator spacing in a GPS receiver" NAVIGATION. JOURNAL OF THE INSTITUTE OF NAVIGATION, FALL 1992, USA, vol. 39, no. 3, pages 265-283, XP002148730 ISSN: 0028-1522 cited in the application the whole document -----	1,11,14, 19,20

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